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THE GAS-HEATING PHASE IN ELECTRICAL BREAKDOWN

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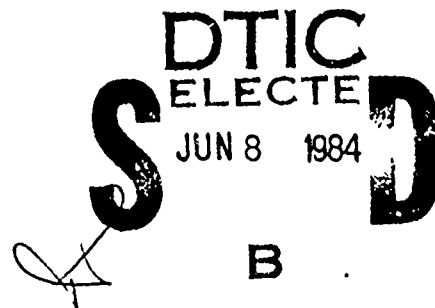1400 Washington Avenue
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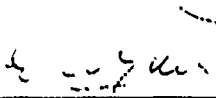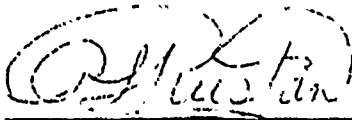WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This report focuses attention on the neglected gas heating stage associated with a spark. A brief review is followed by summaries of recent experimental and theoretical investigations. It is shown that in all cases gas heating is preceded by the formation of a weakly ionized plasma. The transformation to a strongly ionized gas requires additional ionization that can be associated with several different physical processes. In small gaps (3.0 mm) with metal electrodes, the influx of electrons from a cathode spot with at least a single cell is responsible for gas heating. In longer gaps (1 to 3 cm) highly luminous

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ionization waves are produced. These can be reflected at the electrodes and increase the degree of ionization. They are well known but not clearly explained in longer discharges. This stage is followed by the formation of hot filaments either at the electrodes or in mid gap. These seem to be associated with the onset of effective ion-electron interactions. In large surface discharges (~ 1.0 m) the glow and hot channel behind it constitute a stable propagating unit that seems to be controlled by three body electron-ion recombination. The properties of these gliding discharges are similar to those of lightning leaders. In all cases there is strong evidence to support the concept of fluid dynamic effects associated with the hot electron population in the weakly ionized gas. Thus the propagation of stable discontinuities, either strong (shocks) or weak, is shown to be possible.

Foreword

This report describes the results of a research effort sponsored by the Atmospheric Electricity Hazards Group of the AFWAL Flight Dynamics Laboratory (WPAFB-MIPR No. FY145683N0018), the Air Force Office of Scientific Research (AFOSR-MIPR No.AFOSR MIPR 8300007), and the Office of Naval Research. The first two organizations contributed to an on-going research program sponsored by the third (ONR). This allowed the principal investigator, Ernesto Barreto, to visit the Office National d'Etudes et de Recherches Aerospatiales (ONERA) for a ten-month period. The ONR contract number is N00014-80-C-0132 and it is entitled, "Studies of the Behaviour of Coastal Maritime Thunderstorms and Laboratory Investigation of Micro-and-Meso Scale Atmospheric Phenomena."

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This report covers the time period from October 1982 to July 1983. It was submitted to Wright-Patterson Air Force Base in October 1983. Figure 1 is taken from a paper by P. Stritzke, J. Sander, and H. Raether entitled, "Spatial and Temporal Spectroscopy of A Streamer Discharge in Nitrogen." J. Phys D: Appl. Phys., 10, 2285-2300(1977). Figure 2 is from a Thesis Doctorat de 3cme Cycle presented to the Universite Paul Sabatier de Toulouse (Sciences) by George Caures. It is entitled, "Etude des Decharges Transitoires dans les gaz par traitement d'images des cameragrammes de cinematographie ultrarapide." No. D'Ordre: 2589, 17 December 1981. Figure 3 is taken from S. Larigaldie, G. Labaune, and J. Moreau paper entitled, "Lightning Leader Laboratory Simulation by means of Rectilinear Surface Discharges." J. Appl. Physics 52, 7114-7120 (1981).

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I. Introduction

Traditional practical problems associated with the formation of sparks have been ignitions in coal mines and the damage produced by lightning. However, there has been recently an increase in the need to know the behavior and to improve our understanding of high-pressure gas discharges as well as those through solids and liquids. The reasons are associated with a progressively increasing use of insulating plastic materials, the favorable economics of high-voltage transmission lines, costly accidents on ships,[1] aircraft, spacecraft[2] and power lasers,[3] the high efficiency and need for electrostatic precipitators, the increasing sensitivity of micro-electronic circuits to electromagnetic noise and, far more costly, the actual destruction of computer components by the ability of even small sparks to concentrate gigantic energy densities and destroy small regions in a microcircuit.[4]

The number of papers, books and conference proceedings regarding breakdown has, of course, also increased at a fast rate. This is not only because of the need to know but also because recording equipment with better than nanosecond time resolution and fast computers capable of handling complicated equations have become common place. Of necessity most of the work deals with specific problems for which a solution is desired: how to stop ignitions in a super tanker, punctures in a charged dielectric, the suppression of large voltage surges induced by lightning on power lines, the loss of satellites, etc. Each particular problem is interesting and contributes a little to the basic understanding of small and large sparks. Nevertheless, what has become clearly evident is our meager knowledge of basic processes in the latter stages of electrical breakdown in particular, our lack of understanding of the change from weakly to strongly ionized gases that is usually accompanied by the observation of fast luminous waves and leads to gas heating and the collapse of high voltage differences. This report will first review some basic problems and then indicate how our work and that at several other laboratories contribute to the complicated experiment on gliding discharges at the Office National d'Etudes et de Recherches Aerospatiales (ONERA).

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II. Some Basic Problems

From the start the concept of an electron avalanche was known to be deficient to explain a discharge that does not require externally produced electrons and is therefore self-sustained. Thus, Townsend himself introduced the need for an additional ionization process not directly related to the production of new electrons by their collision with neutral atoms or molecules. He thought that positive ions would ionize neutral molecules and introduced his secondary coefficient for ionizaticn. This coefficient has remained in the literature but its physical significance has been shifted to more realistic ionization associated with ionized, excited or metastable molecules interacting and liberating electrons at a surface or in the gas. The current of a self-sustained discharge, I, can be expressed in terms of the distance it travels, x, and or primary α, and secondary γ, Townsend coefficients.

$$I = I_0 \, e^{\alpha x} \, [1 - \gamma(e^{\alpha x} - 1)]^{-1} \simeq I_0 \, e^{\alpha x} \, [1 - \gamma e^{\alpha x}]^{-1}$$

The denominator of this equation incorporates the factor $(1 - \gamma e^{\alpha x})$. Thus when $\gamma e^{\alpha x} \to 1$ the current becomes mathematically infinite. Townsend used this condition to define electrical breakdown. Experimentally it is associated with the upcurving in a straight line plot of the logarithm of the current discharge plotted vs distance. In air at atmospheric pressure and in a uniform field,[5] the current at this stage is of the order of 10^{-10} A, very much smaller than currents of the order of 10 A at which gas heating actually begins and the discharge starts to change into a stable arc. Thus if gas heating and Townsend's breakdown are taken to be equivalent the same physical process is extrapolated by eleven orders of magnitude.

At low pressure the upcurving of the curve is associated with the onset of a steady cold-glow discharge, and the condition $\gamma e^{\alpha x} \to 1$ merely indicates the start of the transition to a different steady discharge mode. Likewise at high pressures and low overvoltages the same condition seems to indicate that there is a transient glow that latter changes into an arc. However, the beauty of avalanches and the simplicity of the mathematical argument have carried Townsend's definition of breakdown into modern reviews.[6] If by dielectric breakdown we understand the actual

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collapse of the applied voltage and the transformation to a hot gaseous conductor across the electrodes the concept is not correct. This was evident from the start because avalanches and their associated secondary ionization were explicitly excluded from an explanation of the glow-to-arc transition.[7] Nevertheless, glows were and are usually considered to be electrical breakdown.

Using cloud chambers it was soon realized that when avalanches reach a critical amplification (10^8 in N_2 at 300 Torr) the space charge field produced by a large difference in velocity between electrons and ions is more effective than that due to the applied voltage for the purpose of propagating ionization into the neutral gas. Thus, streamers develop that travel faster than the drift velocity of the electrons. Whether or not these streamers should be considered to be conducting or dielectric has been a source of controversy which until recently had little direct experimental support. For instance, one of the best established models (Dawson – Winn)[8] assumes a significant separation of charge at the head of the streamer while actual recent measurements[9] indicate that the medium is a weakly ionized gas and consequently the region of charge separation is limited to distances of the order of the Debye length. Initially it was believed that in gas mixtures impurities (e.g. O_2) could be ionized by radiation from the decay of excited molecules. Thus, strategically located seed electrons could be placed just ahead of the high field region at the tip of the propagating streamer. At the present moment this view has been challenged by a multitude of competitive processes with the result that there is no uncontested mechanism responsible for the seed electrons required for the propagation of positive streamers.[10]

The existence of negative (anode directed) streamers in corona discharges has never been clearly demonstrated. By contrast and, somewhat as a surprise, in uniform fields of the order of 2.0 cm in length it has been established that both positive and negative streamers are present, and that the negative streamer travels faster.[11] This is probably because it goes back into a region that is already ionized by the critical avalanche that produced the space charge which launched the streamer. This fact seems to support the concept that streamers should be considered as conductors. Accordingly, it should be noted that if a negative streamer reaches the

anode when the positive is still traveling, the latter accelerates.[12] This indicates an interaction between the cathode and the tip of the positive streamer at a speed very high compared to the streamer velocity ($10^4 - 10^6$ m/sec).

Regardless of small differences in interpretation, pioneering work by Wagner[12] and Tholl[11] in Germany using hydrogen in a uniform field and by Marode[13] in France using positive point-to-plane geometry in air, has proven that, contrary to what was expected, the crossing of a gap by streamers does not immediately involve the formation of a hot channel. Instead as previously noted, a transient glow stage sets in. For a given configuration the duration of the glow stage decreases as the overvoltages increases and as we will see it may completely disappear. In molecular gases (N_2, O_2, H_2) the electron temperature is of the order of 1-4 eV limited by the onset of vibrational excitation of the molecules. The number density of electrons in a streamer is between $10^{12} - 10^{15}$ cm^{-3}. Consequently, the total energy stored in all electrons is a small fraction of the thermal energy of the neutrals and the gas remains cold. This is strikingly demonstrated by the fact that pure corona discharges do not ignite combustible hydrocarbon mixtures.[14] In order to heat the neutrals, the number density of electrons has to increase to values about 10^{17} cm^{-3}. At this number the collision frequency between electrons becomes just as large as that between electrons and heavy particles which include a small (10^{-2}) fraction of ions. However, these have very large Coulomb cross-sections and a real thermodynamic equilibrium with identical particle temperatures is produced in times of the order of 5-10 nsec. The manner in which the electron density increases and whether or not the phenomenon is controlled by the electrodes is not always clear and will be discussed more in detail in this report. What is certain is that the weakly ionized plasma collapses, and that, if sufficient energy is available, the hot plasma produced increases its degree of ionization by at least a factor of ten to values as high as 10^{18} to 10^{19} electrons/cm^{-3} in air. Metal from the cathode evaporates which may provide atoms with a lower ionization potential. Thus the discharge changes to a hot arc whose potential difference is only of the order of the ionization potential of the vapor atoms and whose current is limited by the power supply used.[15] The

discharge sooner or later interacts with electrodes particularly the cathode and becomes affected by metallic properties.

In long positive point-to-plane sparks in air, leaders are produced that exhibit a bluish glowing fan traveling ahead of a bright white region that emits continuum radiation. By contrast, the radiation from the fan is made exclusively of discrete molecular lines thus indicating a low degree of ionization and a high electric field. This radiation is the same as that observed in a streamer or the positive column of a glow discharge. Thus it is assumed that they are all the same physical process, namely ionization by collision of electrons accelerated in an electric field. Clearly the transformation from a weakly to a strongly ionized gas in a leader takes place without the direct influence of nearby metal electrodes. Leaders have been analyzed in terms of two basic models. See Kekez and Savic[16] consider the head of the leader to be a very hot small region in complete local thermodynamic equilibrium. A shock wave is produced that overtakes the incoming high energy electrons in the glowing fan and the leader head regenerates itself by effective Coulomb interactions between the incoming electrons and the hot plasma. The other theory by Gallimberti[17] considers that many negative ions are produced in the glowing region. Electrons are produced by detachment due to Joule heating in the convergent part of the fan. Thus detached electrons rapidly flow to the positive electrode and leave a net positive charge that starts a new corona fan and leads to the formation of a propagating stem whose temperature is of the order of the value required to detach electrons from negative ions ($\sim 2.0 \times 10^3$ °K). Regardless of the actual leader mechanism we want to point out that they have definitely thermally hot channels as evidenced by Schlieren photographs.[18] Also, that they travel at speeds of the order of 10^4 m/sec which are smaller than the speed of streamers.

In steady glow discharges there is a large variety of waves that propagate from anode or cathode and produce standing or slowly moving luminous striations that exhibit potential differences of the order of the ionization potential of the gas. These waves may be self-excited in direct current discharges. They are more pronounced in molecular gases and are associated with spatial resonances of the electron gas in the

discharge. Typically they are not associated with gas heating and the collapse of the glow stage. They have been successfully analyzed using linearized models and have been called ionization waves. There is a large body of literature concerning these waves and we refer the interested reader to a review by Garscadden[19] and a book by Franklin.[20] What should be noted is that these waves clearly exhibit the ability of a glow to sustain wave propagation associated with the electrons.

In all high-pressure discharges there are also fast luminous pulses that travel along the discharge channel but, in contrast to the waves just mentioned, are definitely associated with increasing the degree of ionization in the discharge. The late Professor Loeb indicated that these waves are responsible for maintaining a stepped leader conducting for the time between steps and that they should share the same physics as the lightning leaders.[21] He proposed that they should all be called ionization waves of potential gradient and indicated that even streamers corresponded to one form of these waves. His model of propagation was based on photo-ionization and avalanches. Quite in contrast R.G. Fowler[22] has been, for a long time, proposing the idea that non-linear fluid waves can propagate through the electrons in a gas. Also that with sufficient overvoltage ionization waves may even propagate into a neutral gas as it is actually observed in long tubes at low pressure. In other words it is possible to have a strong discontinuity that ionizes the gas and can move at speeds that range between 10^5 and 10^7 m/sec.

III. Objective

The purpose of the simplistic review just presented is to note that gas heating by electrical discharges at high pressures, together with its associated flash of luminosity (the spark), is a transient phenomenon that occurs after the electrons in the discharge are sufficient in number to be strongly affected by Coulomb interactions. As recently noted in independently prepared reviews by Marode[23] and by the author,[24] it seems that at low overvoltages ($\lesssim$ 35%) there is always a transition to a weakly ionized plasma that is basically no different from a glow discharge. This fact seems to be independent of actual pressure, gas composition and electrode geometry. Thus before heating occurs the electrons in a discharge

are sufficient in number to act as an independent high temperature fluid
that is not in equilibrium with neutrals or ions. Consequently, the con-
cept of Townsend breakdown using a Paschen curve merely indicates a change
to a new short-lived ($10^{-6} - 10^{-7}$ sec) stage in the discharge that is
nevertheless much longer than the time required for electrons to establish
random properties by colliding with neutrals. ($\sim 10^{-12}$ sec). The change
to a glow may irreversibly lead to gas heating but has little to do with
the processes that produce it. Heating comes about as an intrinsic
thermodynamic instability in the plasma which is known to occur at a well
defined critical degree of ionization[11,12,23,24] ($\sim 10^{-2}$ in air corresponding
to $\sim 10^{17}$ electron/cm^3 at atmospheric pressure). What precisely brings
about the increase in electron density to produce a spark is not clear and
may be different under different experimental conditions. For instance,
a small spark is definitely strongly affected by metallic properties of
the electrodes but it is not clear that this interaction plays a major role
in longer sparks and it must be ruled out in discharges that involve only
dielectrics (e.g. lightning). A gas may heat up without evidence of space
waves as the result of a subsonic expansion of electrons from a cathode
spot into the pre-breakdown glow.[25,26] However, if the electrons can be
regarded as a fluid, then it is possible for strong hydrodynamic discon-
tinuities to exist. They will effectively increase the ionization in the
gas. It is even conceivable that a strong shock wave may change the gas
from neutral (instead of weakly ionized) to strongly ionized. This seems
to be what happens at very high pressure or overvoltages. In all cases,
it is clear that the final increase in ionization comes about by isotropic
inelastic collisions of electrons with neutrals and not directly by the
acceleration of individual electrons in the direction of the applied
field. Note that this is basically the same criteria as that postulated
by Loeb to explain the formation of ionizing waves of potential gradient.
He pointed out that these waves are produced whenever the accumulation
of electrons exceeds their ability to diffuse in the gas.[21]

IV. Some Recent Experiments

In the process of clarifying the physics of ignitions we have been
able to show[14] that a minimum ignition energy, that is to say, the minimum
amount of energy required to heat a gaseous mixture to combustion temperature,

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is associated with the ability of the spark to produce electron densities of 10^{17} cm^{-3}. The energies involved are $1-2 \times 10^{-4}$J. Our small sparks are produced in gaps that are smaller than those required to produce an avalanche of critical size. Consequently, no streamers are produced. Instead, the discharge expands over the cathode by photoemission for a time period of $2-5 \times 10^{-7}$ sec. It fills a cylinder of diameter comparable to gap separation with a glow discharge. Then, very suddenly, in times of the order of 5 to 50 nsec practically all of the stored electrical energy goes into the gas, the current reaches a peak value of $\sim$ 10A and the voltage completely collapses. Thus, in a sense, we have isolated the simplest possible manner in which the glow-to-arc transition takes place: the available energy is just sufficient to heat th gas, there are no streamers and there is a glow stage that precedes the gas heating event.[24]

It was soon established that gas heating was directly associated with the formation of a cathode spot as suggested by Cobine[27] as early as 1938 (see e.g. review by Lutz[28]). A direct confirmation of this fact can be obtained by covering the cathode with a thin dielectric material (e.g. a Mylar sheet, or Polaroid coating). It is observed that the onset of ionization occurs at exactly the same electric field as without the dielectric. However, positive ions from the glow rapidly accumulate on the surface and reduce the field in the gap. No cathode spots are produced and no spark occurs. Only when the dielectric has accumulated sufficient charge to sustain a large surface streamer discharge does a spark take place. This, of course, requires energies much larger than the amount required to heat the gas with two metal electrodes. The surface streamer discharge seems to replace the cathode spot.[14]

Even a very carefully cleaned and polished electrode of any metal, including the noble metals, is always coated by a very thin oxide layer that may be patchy or continuous and varies in thickness from 5 to 500 nm.[29] The reason is that the equilibrium vapor pressure of O_2 over a metal surface is of the order of 10^{-10} Torr. Thus, unless very extraordinary care is taken a metal surface always incorporates a dielectric oxide layer. (A fact familiar to people that try to measure work functions). The fact is that the surface of a metal with its associated dielectric coating constitutes a very good capacitor. Some of the theories concerning the

formation of a cathode spot explicitly include changes in this oxide layer.[30] However, the physics of this process is probably in worse shape than that of gaseous breakdown because some of the leading scientists in the field have used convincing arguments to claim that, even conceptually, we simply do not comprehend what happens.[31] Experimentally it is accepted that a cathode spot starts with a process of cold field emission and that it incorporates a characteristic smallest unit of surface known as a Kesaev cell (1-2 μm). We have been able to relate the gas heating event at minimum energy with the formation of at least a single Kesaev cell. Thus it is experimentally clear that gas heating in small gaps is controlled by events that take place at the cathode. If the electrons in the glow constitute a weakly ionized gas then it is possible for them to interact with those emitted from the cathode spot in such a way that the electron temperature increases and the ionization reaches the critical value for gas heating. We have shown that this is indeed the case and that the interaction is compatible with the ability of electrons to behave like an independent fluid.[25] Experiments in N_2 clearly exhibit a region of ionization that is shaped like a cone with its apex at the cathode spot. The angle of luminosity is of the order of 25°. This is about an order of magnitude larger than the cone of a typical avalanche,[34] but exactly of the right size to represent a region of turbulent mixing in a submerged electron jet.[26] (This angle is unique for all fluids).[32] The picture that emerges is then that of electrons from the cathode spot being injected into a weakly ionized glow and producing electron turbulent mixing. This raises the electron temperature and produces further ionization. If this is the case there should exist a needle shaped inviscid core region in the jet that extends from the cathode into the gap. We have obtained photographs that clearly exhibit the existence of this inviscid core region. Not only that, but it has been shown that increasing the capacity results in periodic structures that can be calculated as the characteristic shock structure of an underexpanded supersonic jet.[26] The point being made is that we have good evidence to demonstrate subsonic and supersonic behavior with reference to the electron acoustic velocity ($\sim 7 \times 10^5$ m/sec in N_2 at atmospheric pressure assuming $T_e \sim 1.5$ ev). As the gap length is increased it becomes less evident that the discharge and final gas heating may be controlled by the electrodes.

A particularly clear experiment was reported by Stritzke, Sander and
Raether in 1977.[33] (Contrary to most of the previous work by Wagner,
Tholl and Koppitz in Professor Raether's group this paper is published
in English). They consider breakdown in N_2 at 300 Torr with 20% over-
voltage in a 2 cm uniform field gap, and take into account the fact that
N_2 is not a hydrogen like atom as far as spectroscopic studies are concerned.
About 100 electrons are released from the cathode by a UV flash and start
an avalanche whose luminosity becomes recordable before it reaches its
critical amplification of 10^8 at 14 mm from the cathode in 90 nsec.
(See Fig. 1 taken from their publication). Then anode and cathode dir-
ected streamers propagate from the region where the avalanche becomes
critical. They bridge the gap at 140 nsec.

Starting at 130 nsec three luminous waves are recorded. The first
one follows the cathode directed streamer channel even before the latter
reaches the metal surface. The speed of these waves is recorded as 0.5,
1.8 and 3.6 x 10^6 m/sec. The circuit current shows a rapid increase as
soon as wave propagation starts. It is noted that the luminosity in the
channel starts to increase rapidly as soon as the streamers reach the
electrodes and that the rate at which it grows increases from exp (1.5)
in 2.5 nsec to exp (3.0) in the same time interval but after the passage
of one wave. Thus, the increasing speed of the waves may be associated
with higher conductivity. The luminosity during the wave propagation
stage is exclusively from molecular N_2 line emission. ($T_e >> T_n$) and
the current growth is accelerated much more than in the avalanche-streamer
stage. When the current reaches about 10 A a region 2 mm behind the critical
avalanche (at the "neck" of Allen and Phillips[34] cloud chamber experiments)
becomes thermalized in a few nanoseconds as evidenced by the emission of
continuum radiation. Then a hot thermalized plasma propagates towards
anode and cathode. The current keeps growing to 1800 A when it becomes
limited by the circuit. There are three things we must note about this
outstanding paper. First, that gas heating starts at the same current
($\sim$ 10 A) as what we measure in smaller gaps without streamers. In fact
this current value does not change by changing the overvoltage even though
the whole current growth is accelerated. As noted, the time between the bridging
of the electrodes by the discharge and thermalization decreases rapidly

with overvoltage. Secondly, it must be noted that even in a relatively small gap (2 cm) waves of ionization reflect from either electrode as was originally noted in much larger gaps. Note that they travel in weakly ionized channels, and are more effective for ionization than avalanches or streamers. Thirdly, that a thermalized region propagates from a midgap region toward both electrodes at speeds comparable to those of the ionizing waves in the weakly ionized gas stage. The paper makes no reference to metal lines or cathode evaporation although it probably does occur. For instance Wiese and Augis[35] start to see traces of metal lines at the surface of a gold cathode at 60 nsec in a discharge in Argon at 1 atm. Thus there is evidence of some cathode activity early in the discharge, but in all cases it is clear that the gas gets hot before ionization of metal vapor starts to become effective in the gap. In fact, Stritzke computes an increase in pressure by a factor of 25 in just a few nanoseconds, which is comparable with the time at which we measure a spark to become hot without streamers. It must be emphasized that only electron motion can account for these times, and that even though a streamer stage is produced, it is not clear that the electrodes do not play a significant role.

In positive point-to-plane gaps of 1-2 cm the streamer is produced in a region with a field much higher than that in a uniform geometry configuration. However, once produced the streamer travels in a region of comparatively negligible electric field. It has been shown that in air they can travel for a small distance even in a field free region.[36] Also that they propagate[37] for distances of the order of one meter with a field small compared to that required to start ionization in a uniform field ($\sim$ 7 vs 30 kV/cm). Once they cross a 1 to 2 cm gap streamers lead to a spark with a delay time that decreases with their amplitude.[13] The circuit current during this delay stage is negligible compared to that when the streamer is traveling. After a pause, current again grows very rapidly, as in uniform fields. Bastien and Marode[38] have proposed an explanation for the breakdown process based on the assumption that excited molecules transfer their energy to the neutrals. This transfer together with some Joule heating leads to a small but rapid gas heating of the channel (a few 100's °K) with the net result that the density decreases

and the E/n_n value increases in a cylindrical region outlined by the primary streamer. Consequently, intensified ionization takes place and the spark issues. This model neglects the shielding of the field that would occur if the streamer can be considered to be a good conductor and any possible interaction with the electrodes. It assumes that there is sufficient energy on the excited states to be comparable to the neutral gas thermal energy.

In the past few years the problem has been intensively studied experimentally at the Universite de Pau-Adour by Dupuy, Gilbert and their associates.[39] They have incorporated a Schlieren system together with up-to-date instrumentation to record different stages in the transformation to a spark in positive point-to-plane geometries of the order of 1-2 cm. The Schlieren system does not record the density decrease predicted by Bastien and Marode. Instead, it seems that the channel gets very hot and at high pressure before it even starts to expand. This, of course, agrees with Stritzke's observation in uniform fields. They have also observed that before the collapse of the voltage there exists a stage in the discharge characterized by the formation of "filaments." These propagate from both anode and cathode into the gap and are thermalized. Thus the sequence of events is listed as follows: streamers, cathode activity and cathodic return front, anodic channel or secondary streamer, filaments and spark. We refer the reader to the publications listed as reference 39 for details. There are however some results of these studies that are particularly pertinent. The discharge does not become hot without activity at the electrodes. The anode directed wave has a speed between 0.7 and 5×10^6 m/sec. Its length of travel increases with capacity that determines whether or not the wave dies or crosses the whole gap. This is exactly the same as for our inviscid core jet lengths. It is important to emphasize an, as yet, unreported fact (Dupuy personal communication, 1983): A cathode-directed secondary streamer and the wave from cathode to anode have luminous fronts that meet but pass through each other without any significant change in their propagation characteristics. This is a basic property of solitary waves in fluids. Finally, the spark channel is related to a critical charge density and consequently a critical energy which is determined to be 0.15×10^{-3} J and corresponds precisely to the

minimum energy required to heat the gas in our small sparks without streamers. The nature of the filaments is not clear. Dupuy, et al. suggest that they may be the same as leaders in long sparks. But they may also be associated with the thermalized channels observed by Stritzke to propagate toward the electrodes from the initial region of thermalization behind the critical avalanche as well as to the thermalized inviscid cores from our cathode spots.

The main purpose of reviewing all this experimental work is to demonstrate that in small sparks, just as in large sparks, the final ionization stages that lead to a collapse in the applied voltage are also always associated with the formation of luminous waves. Under many different circumstances these waves propagate at speeds of the order of 10^6 m/sec which is very close to the electron-acoustic velocity $(5\ kT_e/3m_e)^{\frac{1}{2}}$. It makes no difference if the discharge is preceded by streamers or by successive avalanches. In fact, Koppitz[40] has shown that by enhancing photoemission using a CuI cathode coating the luminous wave fronts are no longer filamentary. Nevertheless he measures about the same velocity ($\sim 10^6$ m/sec).

In small gaps it is clear that the electrons that produce the voltage collapse are supplied from the outside of a region that is a weakly ionized plasma. The electrons have maxwellian distributions $[m_e/m_n << \nu_{ee}/\nu_{en} << 1]$, obey an ideal gas law and can be described as collision dominated. ($\bar{t} >> \nu_{ei}^{-1}$; $\bar{l} >> \bar{C}_e \nu_{ei}^{-1}$ where $\bar{t}$ and $\bar{l}$ are typical time and length dimensions, $\bar{C}_e$ is the average electron thermal speed and ν_{ei} is the collision frequency with ions; $\nu_{ei} \sim \nu_{ee}$).

V. Theoretical Approaches

As indicated Fowler[22] and his students have proposed that it is possible for non-linear effects to produce a strong shock-like wave in the electrons. This can propagate as a strong discontinuity into a neutral gas. Thus, he assumes the existence of a step like time independent solution for the system of equations of conservation of mass momentum and energy together with Poisson's equation. He assumes that the electron pressure gradient is the driving force. Consequently, the wave may propagate in or against the direction of the electric field. This has been

experimentally known for a long time (∿ 1920). In contrast to this point of view Albright and Tidman[41] and Klimbeil, et al.[42] have proposed the propagation of a wave driven primarily by a strong electric field (∿ 10^7 v/m in air) into a neutral gas. Photoionization and constant electron temperature are considered to be important for the propagation of this wave.

Since our experiments with small sparks demonstrate that most of the electrons that heat the gas are injected into the spark gap by processes occurring at the electrodes, we can consider the possibility of wave propagation into a weakly ionized gas with the additional restriction that the source term in the mass conservation equation is small compared to all other terms.[43] Thus the weakly ionized gas provides the low pressure electron gas and those coming from the cathode are so numerous that their flux outweighs the ionization taken place. This is in accordance to the fact that inelastic collision frequencies are very small compared to their elastic counterpart ($\nu_{NE} \ll \nu_{ei} \ll \nu_{en}$). The Vlasov-Maxwell system of equations (collision term in Boltzman's equation equal to zero) can be written as a single non-linear matrix equation. When linearized about an initial steady state this equation yields, formally, a standard dispersion equation for the propagation of plane waves proportional to exp[± ($\underline{k}$x-ωt)] for each matrix component (electron density, fluid velocity, temperature and electric field).

$$\omega^2 = c^2 \underline{k}^2 + \omega_p^2 = c^2 (2\pi/\lambda)^2 + n_e e^2/\varepsilon_o m_e \text{ with } c^2 = (5kT_e/3m_e)$$

The group velocity if given by $(\partial\omega/\partial\underline{k}) = c^2(\underline{k}/\omega)$. Thus plane waves propagate provided $[c^2\underline{k}^2 + \omega_p^2 - (2\pi \nu_{en})^2]^{1/2}$ is a real number. That is either $n > (\varepsilon_o m_e/e^2)(2\pi \nu_{en})$ or $\lambda < (c/\nu_{en})$. Consequently there is a critical density or wavelength for propagation that depends on the average electron neutral collision frequency. Using suitable values for air ($\nu_{en} \sim 10^{12} \text{ sec}^{-1}$) it can be shown that waves propagate at either a density lower than the critical thermalization value or for wavelengths of the order of the thickness of the oxide layer at the cathode. (This is, of course, what is experimentally confirmed by the shock wave pattern on the inviscid core structure in the electron turbulent jet experiments).[26] Asano[44] has shown that even for a thermally conducting viscous fluid with electron neutral collisions there are changes in attenuation of the waves but not in the

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reference electron acoustic speed. Consequently, the whole Vlasov-Maxwell system of equations was, again, considered more in detail.[45] The importance of each force term in the momentum equation can be assessed by normalizing the equations and comparing the coefficients in front of each term. The equations are not linearized so that the formation of discontinuities due to the presence of small but finite non-linear terms remains in the mathematical description. It can be formally shown that for a characteristic propagation velocity of $\sim 10^6$ m/sec the driving force term is always, as expected, the electron pressure gradient. The values required for the characteristic time are compatible with the electron-neutral collision frequency that determines their distribution but not with the much smaller ion-electron interaction that determines their thermalization time. The problem needs further clarification because it is associated with the well known divergency of crossections for Coulomb forces and the possibility of multiple interaction between electrons. Nevertheless, it is possible to show that the weakly ionized plasma is a suitable media for the propagation of fluid waves with an amplitude that is either stepped (shocks), S-shaped (satisfy Burger's equation) or even that of a soliton (satisfy non-linear Schrödinger or Korteveg-de-Vries equation). This is, again, as expected from the experimental section.

While we were concerned with analytic mathematical solutions to support the possibility of wave propagation in weakly ionized gases, I. Abbas and P. Bayle,[46] at the Université Paul Sabatier in Toulouse, put numbers into the same system of equations and prepared what the author considers the best hydrodynamic description of the spatio-temporal evolution of density momentum and energy in an electrical discharge. The mathematical formulation includes source terms, thermal and density diffusion, all interactions of electrons with heavy particles and the fact that electrons are not necessarily in equilibrium with the electric field.

By taking into account the finite life time of excited molecules, it is shown that photoionization is not an important mechanism for the propagation of fast ionizing waves ($\sim 10^6$ m/sec) at high pressures. In dense nitrogen (p > 50 Torr) the ionization wave due to photoionization is shown to lag behind the electron collision ionization wave. Thus

irrespective of their actual ability to ionize, photons are emitted too late. A computer solution shows that some of the electrons in the shock front can actually become precursors traveling ahead of the actual front. This is due to thermal diffusion. It is shown that the shock zone cannot be the same as that in a regular shock in a neutral gas. Instead an electron shock is divided into two different regions separated by an electron pressure maximum. This separation is tied down to the absence of anbipolar diffusion that in turn limits the analysis to relatively small electron densities. Nevertheless, it is shown that the two regions comprising a shock are not transient in nature and can be maintained as a propagating structure. Thus, basically, our work is in agreement with that of Bayle and both are in support of the model proposed by Fowler. As far as space waves of ionization are concerned, the often quoted important role of photoionization does not seem to be justified for dense gases (This is not the situation for streamers in gas mixtures). The papers of Abbas and Bayle,[46] like the paper by Stritzke[33] in the experimental section, must be carefully read by all people interested in high pressure discharges.

The research at Toulouse is also tied to experimental results. Thus, a theory has been developed by P. Bayle, M. Bayle and E. Morales[47] to interpret streak camera records. It has been shown that the variations in optical density in a film can be used to evaluate the electric field and the electron density. G. Caumes[48] has prepared a thesis (Doctorate de 3 ème Cycle to appear in J. Appl. Phys., D. 1983), in which streak pictures from discharges in N_2-O_2 mixtures are systematically analyzed using a computer to store the data. The results provide a clear record of the propagation of space waves of ionization. Typically a small perturbation in electric field or electron number density is followed in steps of 0.04 nsec. It is clearly shown that in times of the order of 0.4 nsec and distances of about 0.2 cm, an initial small disturbance grows to be a propagating electric field or electron density maximum. (Note, the speed is about 5×10^6 m/sec). The front is followed by oscillations that look very much like those in collisionless shocks (See Fig. 2 taken for Caumes thesis).

VI. The ONERA Experiment

A large Lucite plate, typically 2-mm thick, is placed in contact with a long (1.05 m), narrow (15 mm), flat (5 mm) grounded metal strip.

Both the Lucite plate and its attached long narrow electrode are supported
perpendicular to the floor. Facing the plate on the side opposite to the
grounded electrode there is a vertical row of metal points that constitute
a comb-like structure (See Fig. 3). These points are not in contact with
the dielectric but instead are attached to a motor and a high voltage
supply. They can move back and forth horizontally in front of the dielectric
plate. Thus corona discharges charge the surface of the dielectric until
enough charge is accumulated to stop the air discharge. Above the level
of the tip of the grounded electrode there is a metal half sphere ($\sim$ 3 cm
diameter) that rests on the charged surface. It is supported by a rod
that goes through the lucite and is connected to one end of a pressurized
spark gap. The other side of this gap goes to the long grounded electrode
through an induction current measuring device. After the surface is
charged and the corona has stopped, the metal comb is removed to one
side and the pressure lowered in the pressurized spark gap. A spark is
produced that grounds the floating metal hemisphere located at the top of
the system. Consequently, a highly overvolted discharge starts over the
surface of the charged dielectric. If the surface voltage is high enough
this discharge will reach the region directly over the metal grounded strip.
Then a bright spark is produced that travels in a straight path following
the region of high charge density determined by the metal strip. This is
the gliding spark. Straight line propagation and a predetermined location
provide ideal conditions for experimental studies. In addition, the speed
of propagation varies between 0.6 and 2.8 x 10^6 m/sec and spectroscopic
analysis shows that this is fast enough to guarantee that any changes in
the dielectric due to the heat produced by the discharge occur after the
front has passed over the region where such a change takes place. Thus
the spark front is exclusively an air discharge that thermalizes and
becomes very hot ($\sim$ 2.4 x 10^4 °K) without the influence of metallic
properties or the control provided by the impedance of an external power
supply. The currents produced are in the range of 20 to 120 A therefore,
the processes taking place may be closely related to the leaders in
lightning. We are happy to see a lower velocity limit that is very
close to the reference electron acoustic speed. The discharge has been
described in publications by Larigaldie, et al.,[49] who emphasize a pre-
liminary model for the physical mechanisms, and by Borgade and Hartmann[50]

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who performed an initial spectroscopic study of a narrow region at half the length of the spark (1.05/2 m). Both Larigaldie and Hartmann are continuing their investigation beyond these preliminary studies. An internal ONERA report was prepared by Larigaldie[51] and a new one is in preparation by Larigaldie and Lagage.

What can be described as an ideal experimental situation namely a sequential display of all processes leading to the formation of a high current hot channel, not affected by electrodes or external circuit has proven to be also a display of our ignorance concerning what is going on. It is therefore, appropriate to describe a little more in detail some of the experimental results. Discharges that propagate over a positively charged dielectric are called negative discharges and those over a negative dielectric positive discharges. One important finding is that these two types of discharges are completely different in character.[49] Positive discharges exhibit strong current oscillations that become stronger as the charge on the surface (corona voltage) increases; they also exhibit strong luminous bands (like striations) behind the traveling front. Streak pictures show that they travel always in steps. Negative discharges exhibit smooth current traces, and there are no repetitive luminous regions behind the traveling front. They are also initially stepped but above a critical voltage travel continuously over the dielectric. Their velocity decreases as they travel over the surface but this has not been carefully measured. The marked difference is obviously associated with the direction in which electrons travel and seems to support Hemmati[52] that negative discharges (proforce waves) are always strong electron shocks. As noted, most of the ONERA effort has been concerned with negative discharges. Hence, unless specifically noted we will assume this is the case.

A plot of the current value at the start of propagation of the gliding spark, I, versus the voltage of the corona points, V_o, provides a parabolic curve $I_o \sim V_o^2$. Since V_o is much higher than the corona threshold value (~ 5 kV) it can be assumed that it is also the starting surface voltage V_o. It is then assumed that the voltage seen by the propagating tip at any other location is the same as that extrapolated from the I_o vs V_o plot using the current that is measured when the discharge goes over the point in question. With this assumption and a spark

velocity, v_s, measured to be linearly proportional to V_o, it is possible to calculate the change in resistance and voltage per unit length along the discharge channel. The analysis[49] considers all the current flowing in the channel to be produced in a corona brush region ahead of the filamentary discharge. The channel has an ohmic resistance proportional to its length which is responsible for the decrease in current as the discharge elongates. The corona brush discharges the capacitor below its surface and feeds the current into a hot channel behind it. The experimental current traces can be reproduced through calculation using V_o and v_s.

The same picture of a corona brush leading to a hot channel is supported by spectroscopic observations made by Borgade and Hartmann[50] along the axis of the discharge. They observe a region 23 mm long where only N_2 molecular line radiation is recorded. The rotational temperature in this region increases gradually to 1500 °K and then very rapidly within a few nanoseconds jumps to 24,000 °K. At this point atomic, N, O and H radiation is observed together with a strong continuum background. Stark broadening of the hydrogen lines is used to determine a maximum electron density of 7.2×10^{17} cm^{-3}. The length of the front associated with molecular radiation (23 mm) seems to be independent of the applied voltage which for 125 kV corresponds to a time interval of 17 nsec. That is, the time changes with voltage but not the spatial dimension of the front. There seems to be some light before this front but since the spectroscopic equipment is about 2 m away the nature of this radiation is not clear. Further along the channel the density and temperature decrease monotonically to 1.5×10^{16} cm^{-3} and $\sim$ 15,000 °K in a time interval of 800 nsec. It is pointed out that this is the same variation observed in lightning. During this last period the intensity of the continuum background decreases and the present of very strong H and C lines together with CN lines evidence evaporation from the dielectric.

A ten-nanosecond exposure frame[51] from an image intensifier located as far away as the spectroscopic equipment ($\sim$ 2 m) exhibits a brush-like structure with several filaments that converge into a bright region that leads through a constriction into a bright stem ($\sim$ 100 μm). This front has lateral dimensions also of the order of 2 cm (See Larigaldie, reference

49, Fig. 9 or 51, Fig. 1). Because of the molecular radiation the discharge in front of the hot region is considered to be a standard equilibrium glow discharge. It is not clear where in the converging luminous fan does the temperature actually increase. However, as noted, the jump occurs at 1500 °K. At this temperature 0^- loses its electron in an average time of 2.5 nsec which is compatible with the observed rise time to 24,000 °K. Consequently, electron detachment is considered to be important as in Gallimberti's leaders (See reference 17, p. C7-212). (It is perhaps worthwhile to note that in times of the order of 10^{-8} sec 0^- is probably the only negative ion that can be obtained because it is produced through dissociative attachment $0_2 + e \rightarrow 0^- + 0$ and it is unlikely that there is time for three body reactions to form other negative ions.) The glow discharge in front of the hot region is considered to have a uniform field $E \simeq 1.3 \times 10^6$ V/m, a constant electron density $n_e = 10^{15}$ cm^{-3}, and an electron temperature $T_e \simeq 2 \times 10^4$ °K associated with the barrier produced by vibrational excitation. Thus a current is produced and Joule heating produces the gradual temperature increase. It can be argued that since the process is transient such a high field and electron density are compatible with each other. However, it must be noted that plasma shielding is not considered.[24] For instance, if the electron temperature is of the order of 2×10^4 °K, the shielding distance near a high voltage region at 125 kV is λ_D (eV/kT$_e$)$^{\frac{1}{2}} \simeq 80$ µm and the time to produce the shielding is $(\omega_p/2\pi)^{-1} \simeq 4 \times 10^{-12}$ sec. Both values are very small compared to experimental values of 2 cm and 2×10^{-8} sec. (λ_D is the Debye length and ω_p the plasma frequency).

It could be argued that since the actual ionization in the brush is only along the bright filaments, the actual effective field over the whole region is higher. At any rate, there seems to be a correlation between the computed values and those obtained from Toepler's laws.[51] This basically indicates that a minimum energy must be deposited in a glow region before it becomes the hot region of a gliding discharge. The actual distribution of the electric field may not be important since only the potential difference and the total length are related to Toepler's laws.

If ionization takes place ahead of the hot channel it will have to occur either through avalanches or through interaction with an isotropic

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electron distribution in the glow discharge region. An avalanche in air at a field of 4×10^6 V/m becomes critical ($n_e/n_{eo} \simeq 10^8$) in a distance of 4 mm and a time of 20 nsec.[53] In that same time the spark front would have traveled (2×10^6 m/sec)(2×10^{-8} sec) = 4 cm, which is ten times the distance required to make a critical avalanche. There is no data to calculate avalanche growth in a much higher field, but it is known that at the critical stage they exhibit electron densities of $\sim 5 \times 10^{15}$ cm^{-3} and that the positive ions left behind slow their propagation.[34,54] The conclusion is that the glow region in front of the hot channel is not maintained by avalanches. Therefore if ionization takes place in the glow region it will have to be by interaction of the flow region itself with the field. This interaction has been postulated by Albright and Tidman.[41] They have shown that in air there can be an interaction between a very high field (4×10^7 V/m) and a weakly ionized plasma ($n_e \sim 10^{15}$ cm^{-3}; $T_e \sim 1.7$ eV). This tends to produce filamentary channels that propagate at speeds of the order of 10^6 m/sec. The front thickness is of the order of 10^{-5} cm, but since the analysis is based on an energy balance they do not consider any specific ionization mechanism or gas heating. A follow-on paper[42] considers photoionization as the ionization process, but, as noted, this can be ruled out based on Bayle's calculations. Thus their work can account for the filamentary nature of the corona brush but does not consider the actual ionization process taking place.

Regardless of the actual ionization mechanism in the flow it has to occur in a time compatible with the observed distance and velocity: 2 cm and 10^6 m/sec. That is to say ionization has to occur in times of the order of 10^{-8} sec. Irrespective of how the front propagates it is necessary to consider if it is possible to have ionization within the glow in this short time. The ionization frequency, ν_i, for electrons with a maxwellian distribution (guaranteed by the condition $\nu_{ee}/\nu_{en} \gg m_e/m_n$) can be calculated. (See e.g. Abbas and Bayle[46] p. 654 or Larigaldie[51] p.29). Assuming an ionization potential of 16 eV and the ions to be at room temperature (T_e in eV).

$$\nu_i = 1.66 \times 10^{11} \, T_e^{1/2} (1 + T_e/8) \exp(-16/T_e)$$

From this equation we can calculate the following table:

ν_i^{-1}/sec	1.8×10^{-7}	1.0×10^{-8}	1.7×10^{-9}	5.2×10^{-10}
T_e/eV	1.5	2.0	2.5	3.0

It is clear then that within times of 10^{-8} sec electrons in a glow of energy larger than 2.0 eV can reproduce each other. It can even be shown that, as in Gallimberti's leaders, the glow may be in equilibrium with a dissociative recombination process $[e + (XY)^+ \rightarrow X + Y]$ provided $n_e \geq 2.1 \times 10^{15}$ cm^{-3}. This is the value used by Albright and Tidman, Larigaldie and ourselves and corresponds to those actually measured in streamers by Wagner and Tholl. It is concluded that a filamentary glow with $T_e \geq 2.0$ eV and $n_e \geq 10^{15}$ cm^{-3} is compatible with the glow in the gliding discharge. But again a maxwellian distribution implies effective Coulomb shielding and the formation of sheaths.

At this stage the ONERA experiment is necessarily suffering from a high ratio of interpretation to experimental data. Just the same as in other sparks, it is not clear how the electrons become sufficient in number to heat the gas. Bastien and Marode's mechanism of gradual heating can be ruled out on a time basis alone. There are no Dupuy's filaments or our cathode spots to provide the change. A process associated with an ion acoustic instability has been suggested but we fail to see how this can arise in a collision dominated gas ($\nu_{ee} \ll \nu_{en}$). Even if an ion acoustic wave can be produced, its speed is of the order of 3×10^3 m/sec roughly three orders of magnitude slower than the spark velocity. It could be argued that since the spark velocity has a lower limit that is comparable to the electron acoustic speed the whole process is associated with a supersonic electron shock. However, we are not aware of any description actually leading to gas heating and should point out that even though Fowler has assumed the existence of these shocks their true nature and indeed their existence is just becoming clear. We would strongly recommend that electron density measurements be made ahead of the hot region. (In the A and B periods of Borgade and Hartmann,[50] or the AB and BC of Larigaldie[51]). An important finding that will be described in forthcoming publications by Larigaldie is the possibility that gas heating may be

closely associated with superelastic collisions and three body electron-electron recombination ($e + e + X^+ \rightarrow e + X$). This process allows the neutrals to get hot while supplying energy to the electron gas. This seems to be the process that leads to a nearly completely ionized gas, and is compatible with experimental time and temperature changes seen by the spectroscopic study. Finally it should be noted that there has been recently a lot of speculation[55,56] concerning the possibility of very fast ($\sim$ 500 eV) run-away electrons in highly overvolted gaps and in lightning. A gliding discharge could be easily adapted to look for them, for instance, by placing a sensor just below the Lucite surface.

VII. Conclusions

There is evidence that in all sparks, irrespective of pressure and geometry, gas heating is preceded by the formation of a glow discharge. This includes highly overvolted long gaps and surface discharges in which the glow travels ahead of a hot thermalized region. In all cases, the glow constitutes a weakly ionized channel with sufficient electron temperature and density to reduce electrical forces within the region where it exists. In small sparks the glow fills the whole inter-electrode region before any gas heating occurs. Then processes associated with the glow-electrode interface interact with a primarily isotropic distribution of electrons in the gap. The electron energy increases and the degree of ionization also increases to the stage where Coulomb interactions with heavy particles (ions) becomes important. The possibility that gradual heating reduces the gas density and increases the ionization rate is not supported by experimental evidence. On the other hand, the interaction of electrons from the cathode with those in the gap, the existence of waves of potential gradient that reflect at the electrodes and the formation of hot filaments associated with either electrode has been clearly demonstrated. In long laboratory sparks both the leading glow and the hot gas region that follow it, propagate at speeds of the order of 10^4 m/sec and involve currents of the order of 1 A. The transition from a glow to arc is not understood, as evidenced by mutually exclusive models based on either shock waves that overtake high energy electrons or, instead, comparatively low energy electrons undergoing attachment and detachment. The degree of ionization in the leader is small and full ionization becomes evident only with the return stroke.

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Highly overvolted discharges over charged dielectrics travel at speeds of the order of 10^6 m/sec with currents of 100 A. They involve hot channels that seem to be fully ionized as indicated by initial spectroscopic studies. Superelastic collisions and three body electron-electron-ion recombination may play an important role in these discharges that exhibit characteristics similar to lightning leaders: electron densities, time variation, current magnitude and speed. This last one is of the order, or slightly higher than the electron-acoustic speed in the weakly ionized plasma ahead of the hot region. It suggests the existence of an electron shock. The actual transition from glow to hot channel is again not clear but the ability of these surface discharges to display all phenomena at a predetermined location makes them a powerful experimental tool. The ONERA sparks are produced using extremely high voltages ($\sim$ 125 kV). However, the critical parameter is the charge density and it is also possible to produce similar discharges using smaller voltages and thinner dielectrics. This has been demonstrated by Blythe and Carr.[57]

It must be stressed that although in all discharges the transition from a glow to a hot channel is not clearly understood, it most certainly involves interactions at a degree of ionization where Coulomb forces between electrons are important. The concept of independent electrons interacting with an electric field is not appropriate at this stage and must be replaced by that of collective interactions in a plasma fluid.

From a practical point of view a streamer or glow discharge over a thin dielectric has the possibility of puncturing through and establishing a cathode or anode activity that may then heat the region above the dielectric. This is obviously related to the problem of attachment of discharges to painted, or epoxy covered metal surfaces. There are several practical examples that can be listed to indicate the importance of these processes. First is the fact that aircraft seems to be more vulnerable to lightning discharges when the plane travels in a positively charged cloud.[58] This may be related to the fact that weakly ionized discharges produce a cathode region from which a strong wave can be launched. (Only strong electron discontinuities, shocks, are possible with negative discharges). Again there is evidence that the process of dissociative attachment ($O_2 + e \rightarrow O^- + O$) produces discontinuities in lasers

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and that at atmospheric pressure the disturbance travels at about the electron-acoustic velocity.[3] There is the problem of surface discharges over thin dielectrics associated with thermal blankets in satellites. Balamin, et al.[59] have reproduced satellite conditions and bombarded with electrons (20keV) a thin (50 μm) Kapton dielectric with an aluminum backing. Very strong discharges are produced that follow surface disturbances associated with brushing or rubbing. Discharges can then be made to follow straight paths. Their average speed is 7.1×10^5 m/sec. Even a very "clean" surface in the presence of a hot plasma can lead to the production of cathode spots that contaminate the plasma and interfere with the operation of a reactor.[60]
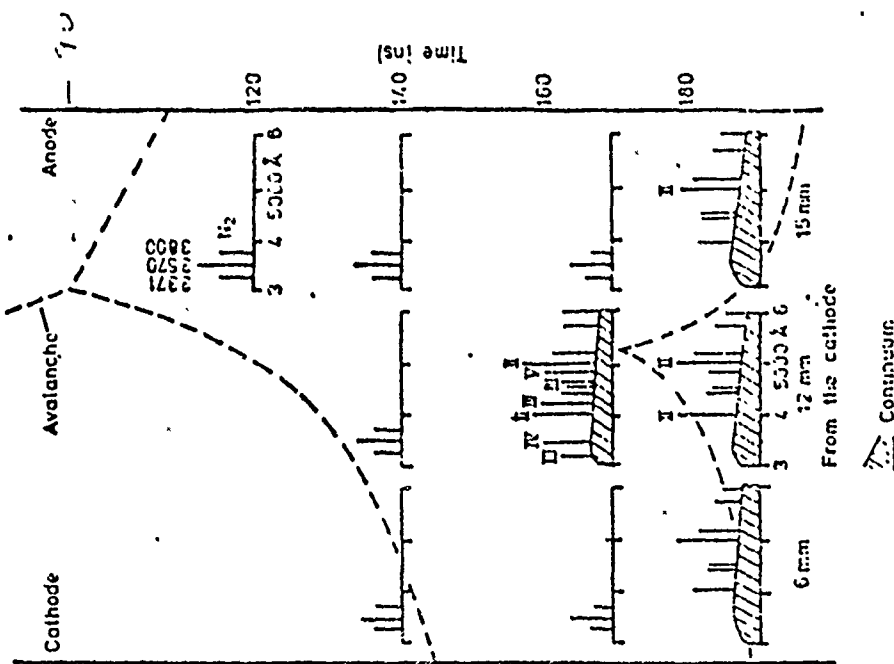
Figure 5. Current as function of the time: (1) theoretical electron current during the avalanche stage, calculated by equation (5); (2) current calculated by integrating measured electron densities (Equation 6); (3) measured current. Besides the avalanche and the streamers the observed ionization waves are drawn (dashed lines in the schematic streak picture).

Figure 1. Schematic spectra in N_2 emitted from the discharge at different times and at different distances from the cathode (6, 12, 15 mm). A streak picture drawn by the dashed lines gives a survey of the different stages of the discharge.
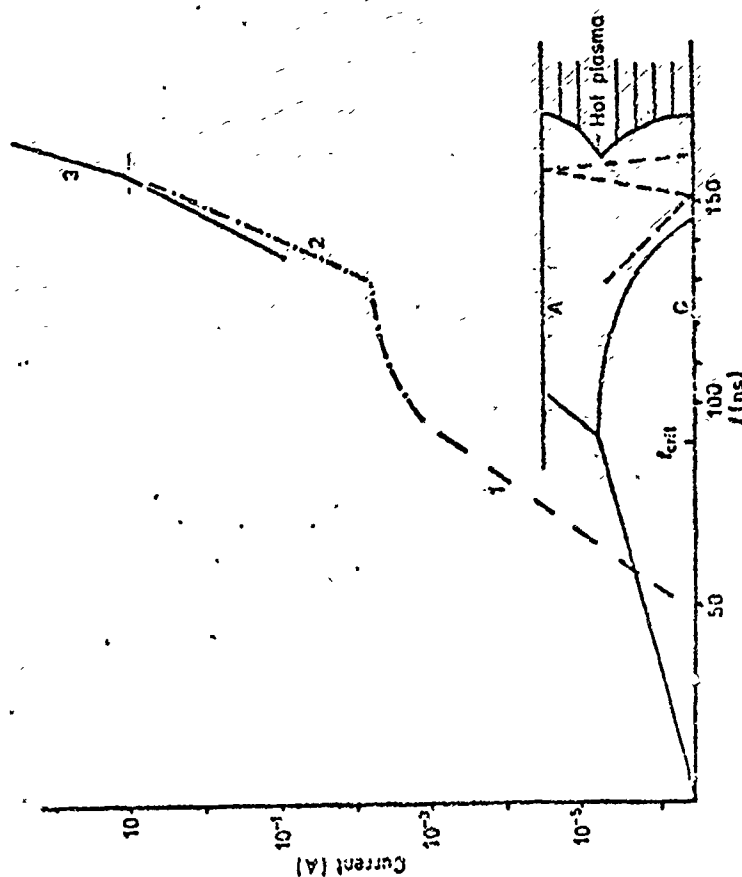
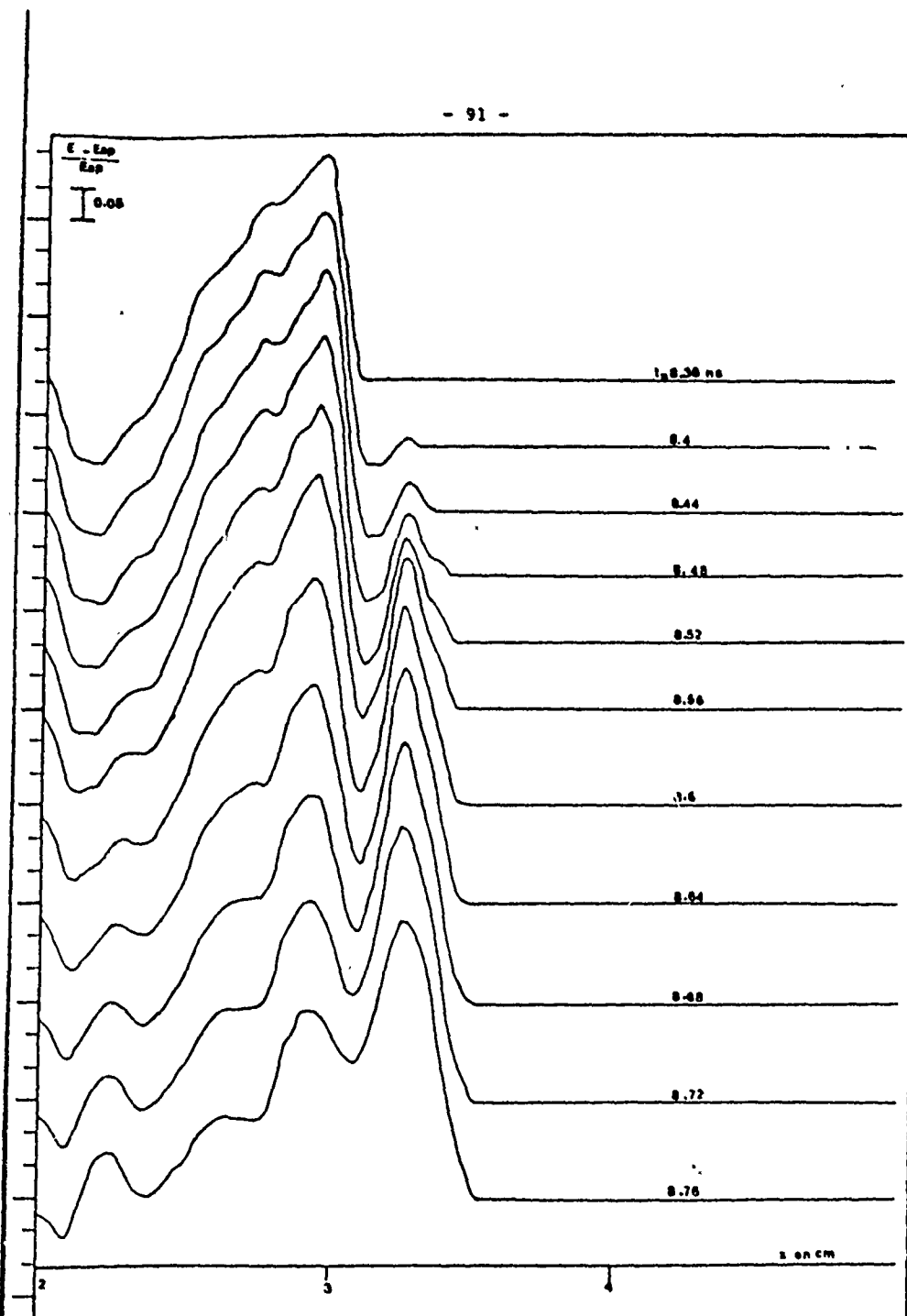Figure 1. Reproduced from reference 33

FIGURE IV-12 : EVOLUTION SPATIO-TEMPORELLE DU CHAMP ELECTRIQUE DANS UNE DECHARGE AZOTE-OXYGENE (10 %) p = 125 Torr.

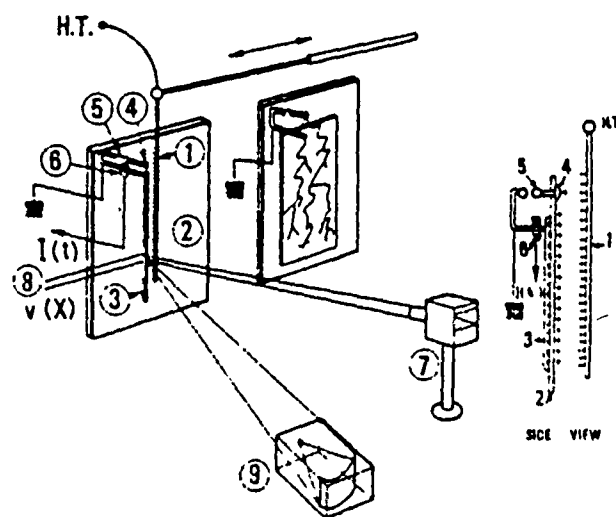Figure 2.   Reproduced from reference 48

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FIG. 1. Experimental setup: (1) Metallic comb (high voltage). (2) Dielectric slab. (3) Metallic strip (grounded). (4) Floating electrode. (5) Spark gap. (6) Current probe. (7) Electro-optical image converter. (8) Optical fibers. (9) Spectroscope.

Figure 3.   Reproduced from reference 49

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REFERENCES

1. Bass, R.L., T.E. Owen and F.T. Dodge. Bulk Carrier Operations Safety Enhancement Project. U.S. Dept. of Commerce, Natl. Technical Information Service, PB-256 188, June 7, 1976.

2. Space Charging Technology. NASA Conference Publication 2182 (AFGL-TR-81-0270). Conf. U.S. A.F. Acad., Colorado Springs, Nov. 12-14, 1982.

3. Douglas-Hamilton, D.H. and S.A. Mani. J. Appl. Phys., 45, 4406 (1974).

4. Chase, E.W. Electrostatic Discharge Damage to Integrated Circuits. Invited Paper, Electrostatics 83. Inst. of Physics Conference, Series number 66, St. Catherine College, Oxford, UK, 13-15 April 1983.

5. Loeb, L.B. Basic Processes of Gaseous Electronics. Univ. of Cal. Press, Berkeley, California, 1955.

6. Dutton, J. in Electrical Breakdown and Discharges in Gases. E.E. Kunhardt and L.H. Luessen, Eds. NATO ASI Series, Vol. 89a, Plenum Press, NY, 1983.

7. Loeb, L.B. Fundamental Processes of Electrical Discharge in Gases. Wiley, NY, 1939.

8. Dawson, G.A. and W.P. Winn. Z. Phys., 183, 159 (1965).

9. Geary, J.M. and G.W. Penney. Phys. Rev. A., 17, 1483 (1978).

10. Sigmond, R.S. and M. Goldman. Electrostatics 83. Inst. of Physics, Conf. Series Number 66, 81(1983).

11. Tholl, H., Z. Naturf. 19a, 346 (1964); 19a, 704 (1964); 22a, 1068 (1967); 25a, 420 (1970).

12. Wagner, K.H. Z Phys. 189, 465 (1966).

13. Marode, E. J. Appl. Phys., 46, 2005 (1975); 46, 2016 (1975).

14. Barreto, E., S.I. Reynolds and H. Jurenka. J. Appl. Phys., 45, 3317 (1974).

15. Pfender, E. in Gaseous Electronics, Vol. I, Electrical Discharges. M.U. Hirsh and H.J. Oskam, Ed., Acad. Press, New York, 1978.

16. Kekez, M.M. and P. Savic. in Electrical Breakdown and Discharges in Gases. E.E. Kunhardt and L.H. Luessen, Eds. NATO ASI Series, Vol. 89a, Plenum Press, New York, 1983.

17. Gallimberti, I. J. de Physique, Colloque C7, Supplément au No. 7, Tome 40, Juillet 1979, page C7-193.

18. Dupuy, J., A. Gibert, P. Domens, B. Hutzler, J.P. Riu, F. Edlinger. 399/RGE-5/81-Mai, 1981.

19. Garscadden, A. in Gaseous Electronics, Vol. I. Electrical Discharges, M.N. Hirsh and H.J. Oskam, Eds., Acad. Press, NY, 1978.

20. Franklin, R.N. Plasma Phenomena in Gas Discharges. Clarendon Press, Oxford, 1976.

21. Loeb, L.B. Science 146, 1417 (1965); J. Geophys. Res., 71, 4711 (1966); J. Geophys. Res., 73, 5813 (1968).

22. Fowler, R.G. Adv. in Electronic and Electron Physics. 20, 1 (1964); 35, 1 (1974); 41, 1 (1976).

23. Marode, E. in Electrical Breakdown and Discharges in Gases. E.E. Kunhardt and L.H. Luessen, Eds. NATO ASI Series, Vol. 89b, Plenum Press, New York (1983).

24. Barreto, E. in Encyclopedia of Chemical Processing and Design. J.J. McKetta and W.A. Cunningham, Eds., 17, 426, Marcel Dekker, Inc., New York (1983).

25. Barreto, E. Electrostatics 1979 (Inst. of Physics, Univ. of Reading, Berkshire London 1979). p. 135.

26. Jurenka, H. J. Appl. Phys., 53, 6115 (1982).

27. Cobine, J.D. Phys. Rev., 53, 911 (1938).

28. Lutz, M.A. IEEE Trans. Plasma Sci., PS-2, 1 (1974).

29. Roberts, M.W. and C.S. McKee. Chemistry of the Metal-Gas Interface. Clarendon Press, Oxford, Chpt. 11 (1978).

30. Guile, A.E. and B. Jüttner. IEEE Trans. Plasma Science, PS-8, 259 (1980).

31. Ecker, G. in Vacuum Arcs. J.M. Lafferty, Ed., John Wiley, New York (1980).

32. Landau, L.D. and E.M. Lifshitz. Fluid Mechanics. Addison-Wesley Pub. Co., Reading, Mass. (1959), p. 133.

33. Stritzke, P., I. Sander and H. Raether. J. Phys. D: Appl. Phys., 10, 2285 (1979).

34. Allen, K.R. and K. Phillips. Proc. Roy. Soc. A, 274, 163 (1963).

35. Wiese, L.L. and J.A. Augis. J. Appl. Phys., 48, 4528 (1977).

36. Winn, W.P. J. Geoph. Res., 70, 3265 (1965); J. Appl. Phys., 38, 783 (1967).

37. Phelps, C.T. J. Geophys. Res., 70, 5799 (1971); J. Appl. Phys., 47, 2929 (1976).

38. Bastien, F. and E. Marode. <u>Gaseous Dielectrics</u> III. Pergamon Press, 1982. See also. J.P. Boeuf and E. Marode. J. Phys. D: Appl. Phys., <u>15</u>, 2169 (1982).

39. Bertault, P., J. Dupuy and A. Gibert. J. Phys. D: Appl. Phys, <u>10</u>, L219 (1977); Dubois, J., J. Phys. D: Appl. Phys. <u>13</u>, 405 (1980); Dupuy, J. and A. Gibert, J. Phys. D: Appl. Phys., <u>15</u>, 655 (1982); <u>16</u>, 379 (1983); Gibert, A., J. Dupuy, M. Bayle and P. Bayle, J. Phys. D: Appl. Physics, <u>16</u> (1983). (in print)

40. Koppitz, J. J. Phys. D: Appl. Physics, <u>6</u>, 1494 (1973).

41. Albright, N.W. and D.A. Tidman. Phys. Fluids, <u>15</u>, 86 (1972).

42. Klingbeil, R., D.A. Tidman and R.F. Fersnler. Phys. Fluids, <u>15</u>, (1969) (1972).

43. Barreto, E., H. Jurenka and S.I. Reynolds. J. Appl. Phys., <u>48</u>, 4510 (1977).

44. Asano, N. J. Phys. Soc., Japan, <u>36</u>, 861 (1974).

45. Jurenka, H. and E. Barreto. J. Appl. Phys., <u>53</u>, 3581 (1982).

46. Abbas, I. and P. Bayle. J. Phys. D: Appl. Phys., <u>14</u>, 649 (1981); <u>14</u>, 661 (1981).

47. Bayle, P., M. Bayle and E. Morales. J. Phys. D: Appl. Phys., <u>13</u>, (1980).

48. Caumes, G. "Etude des Decharges Transitoires dans les gaz par traitement d'images des cameragrammes de cinematograp².e ultra-rapide." esis Universite Paul Sabatier de Toulouse. N° D'ordre 2589. To appear in J. Phys. D: Appl. Phys. (1983).

49. Larigaldie, S., G. Labaune and J.P. Moreau. J. Appl. Phys., <u>52</u>, 7114 (1981); Larigaldie, S., J. de Physique. Collque No. 7, C7-429 (1979).

50. Borgade, M.C. and G. Hartmann. J. Appl. Phys., <u>53</u>, 8568 (1982).

51. Larigaldie, S. "Simulation D'un Foudroiement-Analyse des Mecanismes Associes a la Decharge." ONERA, RF 5/7236 PY, 25 Août, 1982.

52. Hemmati, M. "The Exact Solution of the Electron-Fluid Dynamical Equations." Ph.D. Dissertation. Univ. of Oklahoma, 1983.

53. Wagner, K.H. Z. Phys., <u>241</u>, 258 (1971).

54. Raether, H. "Electron Avalanches and Breakdown in Gases." Butterworths, Washington, D.C., 1964.

55. Kunhardt, E.E. in Electrical Breakdown and Discharges in Gases. E.E. Kunhardt and L.H. Luessen, Eds. NATO ASI Series, Vol. 89a, Plenum Press, New York, 1983.

56. Parks, G.K., R.J. Spiger, B.H. Mank and J. Chin. EOS Trans. Amer. Geophysical Union, 61, 978 (1980).

57. Blythe, A.R. and G.E. Carr. J. of Electrostatics, 10, 321 (1981).

58. Pitts, F.L. AIAA 19th Aerospace Sciences Meeting. Paper No. 81-0083. (Conference held in St. Louis, MO, January 12-15, 1981).

59. Balamin, K.G., M. Gossland and R.D. Reeves. Proc. Intl. Symp. on Spacecraft Materials in Space Environment. CNES, ESA and CERT. Toulouse, France, 8 to 12, June 1982 (ESA-SP-178).

60. Johnson, C.T., A. Lee and G.S. Smeltzer. J. Appl. Phys., 52, 6543 (1981).